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# Integrated collector storage solar water heater with compound parabolic concentrator – development and progress

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ABSTRACT

This paper presents up to date developments in integrated collector storage solar water heater (ICSSWH) using compound parabolic concentrator (CPC) collector. Performance of integrated compound parabolic concentrator storage solar water heater (ICPCSSWH) is affected by various parameters such as positioning and arrangements of water tanks, reflector types, absorber surfaces, glazing and other design parameters. The various designs of ICPCSSWHs and their performance analysis are reviewed. Recent developments in CPC based ICSSWH show a hopeful design to consume solar energy as a reliable heating source for water heating applications. But, by its collective collection and storage function undergoes significant thermal losses to ambient, particularly at non-collection periods.


**Contents**



## 1. Introduction

Solar energy is a world's most prosperous energy source. It is free, clean and safe compared to fossil fuels. Successful proven

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**Nomenclature**

| | |
|---|---|
| $A_a$ | aperture surface area ($m^2$) |
| $A_s$ | total external surface area ($m^2$) |
| C | concentration ratio |
| $\Delta T_{m,\,N}$ | temperature difference during night (°C) |
| $T_{abs}$ | absorber temperature (°C) |
| $V_T$ | storage tank volume ($m^3$) |
| DTS | double tank system |
| STS | single tank system |

*Greek letter*

| | |
|---|---|
| $\theta_c$ | collector half-acceptance angle (degrees) |
| $\varepsilon$ | emissivity |

technologies are available for water heating, air heating, drying, space heating, cooling and power production. Space heating is the significant building energy user in cold climate countries. Conventional space heating technologies are having an impact on $CO_2$ emissions, as well as on safety of energy supply. Space heating with solar energy has been the subject of research and progress since 1938, when MIT built its first solar liquid house. Afterwards in 1943 and 1957, Dr G. O. G. Lof installed a few solar heating systems using air as the heat transfer fluid. Since then a number of designs of solar space heating systems are developed. Solar space heating is not only environmentally friendly but requires minimum maintenance and operation cost compared to conventional methods. In 2010, the worldwide installed capacity of solar water heating systems was 160 GW and increased to 185 GW in 2011 [1]. Because of continuous research developments, solar water heating is now more sustainable and efficient and economical in larger scale. Domestic water heating is struggling to get the sustainable position because of its higher cost. Different types such as, flat plate, evacuated tube, and compound parabolic concentrator collectors are used in a domestic solar water heating system. Normally, in flat plate and vacuum tube water heaters, collector and storage tank are two separate parts. An integrated collector storage (ICS) technique is adopted to make the system simple and economical [2].

In integrated collector storage solar water heater (ICSSWH), solar collector and water storage tank are integrated as a single unit. It is simpler in construction, lower in cost compared to flat Plate or vacuum tube thermo siphon type water heaters and capable of fulfilling hot water demand of 100–200 litres per day [3]. Since, the outer surface of the water storage tank has to receive radiation, it cannot be thermally insulated. Hence, heat loss to surrounding during night time is high [4]. Various investigations were carried out to improve the thermal performance by reducing this loss. Flat plate and concentrating non-imaging collectors have been used in these integrated solar water heaters. In 2006, Smyth et al. [5] have reviewed the developments of different types of integrated collector storage solar water heaters. Henderson et al. [6] have studied the performance variations of flat plate collector type ICSSWH for various inclinations.

The performance of the ICSSWH can be improved by employing compound parabolic concentrator (CPC) collector. Compound parabolic concentrators (CPCs) play a vital role in the low temperature applications. Most of the beam and diffuse radiations can be collected and reflected on the absorber surface [7]. ICSSWH with flat type storage tanks require well-built structure to resist the pressure of water mains. The cylindrical water tanks can be directly connected to the water mains [8]. In 2004, Kalogirou [9], reviewed the applications of different types of solar collectors and also presented the developments in CPC. Recently Shukla et al. [1] reviewed the developments in solar water heaters and also presented the progresses in solar water heaters and highlighted the design developments in CPC. This work critically reviews the research progresses in the CPC and its development in solar water heating which has not been reported so far.

## 2. Practical developments of the compound parabolic concentrators

The major objective of using concentration in solar thermal collectors is to enhance the performance by reducing heat losses. Nevertheless, use of a spectrally selective coating and evacuated absorbers reduced a considerable quantity of heat losses. Unlike other solar concentrators, CPCs provide efficient conversion of solar energy to thermal energies at temperatures well above 200 °C without requiring elaborate tracking system. The selective coatings with an emittance, approximately 0.1 or less significantly suppress the conduction and convection losses. The vacuum insulation in the infrared region of $1.33 \times 10^{-4}$ Pa or less reduced greatly these losses. Hence the low concentration achievable with CPCs results in a collector with excellent thermal efficiency for a stationary non-tracking collector. Over the past 30 years, researchers have worked on the design and development of CPC incorporated with non-evacuated and evacuated absorbers. The forthcoming sub Sections (2.1–2.3) details, the various developments of CPCs over the years and also their potential applications.

### 2.1. CPCs with non-evacuated absorbers

In 1960, Winston discovered CPC and it was accepted for solar energy collection in the USA in 1974 [10]. CPCs are non-imaging concentrators and they have the capability to reflect all the incident radiation to the absorber [1]. The schematic diagram of a CPC is shown in Fig. 1. It consists of two different parabolas (A and B), the axes of which are inclined at an angles $\pm\theta_C$ with respect to the optical axes of this collector. The angle $\theta_C$, is called as a collector half-acceptance angle. The lower portions of the CPC reflector are circular (BC and CD), while the upper portions (AB and ED) are parabolic [9].

A fully stationary CPC ($C$=1.6) with a non-evacuated absorber ($\varepsilon$=0.9) delivered the thermal efficiency of 19.7% at $T_{abs}$= 110 °C. Comprehensive treatment of radiation and convection heat losses through a CPC incorporated with a flat absorber was discussed by Rabl [11]. Winston et al. [12] confirmed that the conduction losses between absorber and reflector can be reduced by creating gaps between them. The results showed that the modified design considerably reduced conduction losses. Various practical problems in the design of CPCs such as the choice of a receiver type, optimum method for introducing a gap between receiver and reflector to decrease the optical as well as thermal losses and the effect of a glass cover around the receiver were discussed by Rabl et al. [13].

The shape of the absorber has a significant effect on the performance of CPC. To enhance the thermal and optical performance of CPC, different shapes of absorbers were proposed [14–20]. Use of a CPC solar collector with a curved inverted-Vee absorber fin was proposed by Norton et al. [14], and found that the modified absorber geometry can significantly reduce the gap optical losses. Keita et al. [15] compared the performance of two similar CPCs with single and segmented absorbers. The results confirmed that the performance of the segmented absorber was

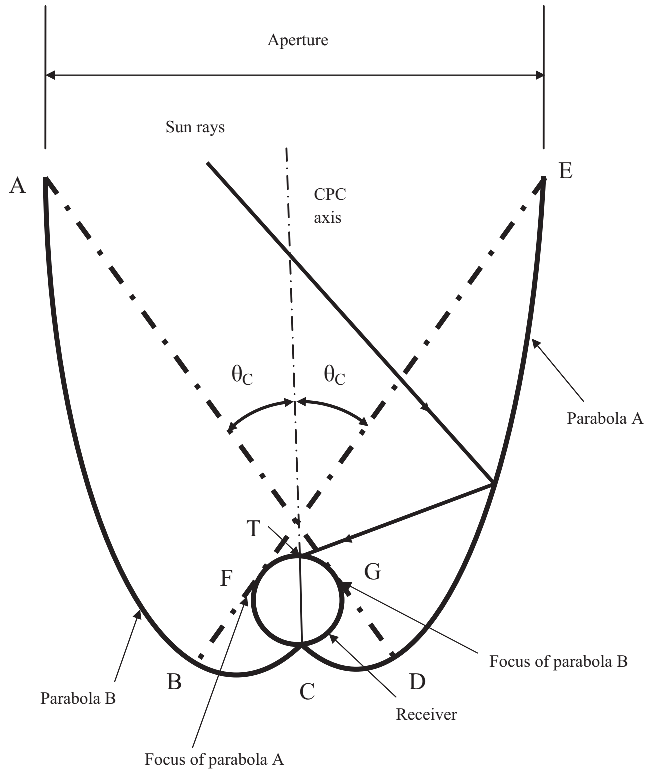


**Fig. 1.** Schematic diagram of a CPC solar energy collector [9].

about 13% higher compared to the non-segmented absorber. Carvalho et al. [16] presented an analysis of a CPC solar collector with an inverted V shaped receiver. The results show that system could perform better than flat plate collectors and evacuated tubes. Tripanagnostopoulos et al. [17] presented an analysis on CPCs with four channel absorbers. These absorbers could attain effective operation at a temperature in the range of 100 to 200 °C. Kothdiwala et al. [18] carried out experimental studies on an asymmetric inverted absorber line axis compound parabolic concentrating collector (IACPC) under a solar simulator. It was reported that IACPC could achieve a maximum stagnation temperature of 109 °C and 157 °C with and without water, respectively in the absorber. Tripanagnostopoulos et al. [19] designed and investigated a non-evacuated stationary CPC with flat bifacial absorbers. Experimental results showed that solar collectors had obtained maximum efficiency of about 0.71. Several experimental studies were carried out on the CPC solar collector to improve its thermal performance. Cairo et al. [10] designed and tested a refrigerant charged CPC under non-boiling, boiling and superheated conditions. They concluded that the performance of the refrigerant charged CPC was better than a flat plate solar collector. Khonkar and Sayigh [20] created multi-cavities with high solar intensities at the circumferential area of the tubular absorber of a CPC, to reduce the radiation losses. Eames and Norton [21] introduced a baffle into the cavity of a non-evacuated CPC. The result shows that convection heat loss and optical efficiency could be considerably decreased.

To improve the performance of the CPC futhur, Eames and Norton [22] presented a parametric analysis of heat transfer in CPCs and discussed about the effects of angular inclination and acceptance angles on free convection within the cavity. They also developed a correlation for the average Nusselt number with respect to Grashof number that considered acceptance angle and angular inclination. The effect of the angle of axial inclination of an east–west oriented, symmetric non-imaging CPC studied by Norton et al. [23] and they also calculated the convection, radiation, conduction and overall heat transfer coefficients and system efficiency for different angles of inclination, concentration ratios and insolations.

Numerous theoretical studies were carried out on the CPC solar collector, to investigate its thermal performance. A numerical approach utilizing a “Finite Element Method” was carried out by Chew et al. [24] to estimate the laminar free convection in a CPC. It was found that the maximum heat transfer rates occurred when the tilt angle was about 60°. Tchinda et al. [25] used numerical analysis to investigate the thermal performance of the axial heat transfer in a CPC collector. Performance parameter such as the inlet temperature and mass flow rate were analyzed. A good agreement was observed between predicted and experimental results. Tchinda and Ngos [26] studied about the thermal performance of a CPC solar collector with a flat one sided absorber. It was concluded from the study that selective coated absorber surface gave better performance than the black painted one. Recently, a study performed by Tang et al. [27] based on theoretical analysis shows that when a beam radiation enters CPC at an incidence angle nearly zero to the aperture, a fraction of solar radiation that arrive the absorber undergoes more than two reflections on both reflectors of the CPC, but the fraction of solar radiation that enter the absorber after more than three reflections was significantly smaller.

Recently, some of the novel types of CPC were proposed by different researchers. Kaiyan et al. [28] have designed an imaging type of multi-curved surface compound concentrator. It consists of a parabolic and a flat contour. This novel collector could transmit the reflected rays to the forward instead of backward as in the traditional parabolic concentrators. In 2013, the CPCs with polygonal apertures were proposed by Cooper et al. [29]. The optical performance of CPCs containing n-sided polygonal inlet and outlet apertures was investigated using a Monte-Carlo ray-tracing method. Use of polygonal CPCs has also reduced the manufacturing cost, when compared to revolved CPC.

### 2.2. CPCs with evacuated absorbers

In 1970, Argonne National Laboratory designed a first generation of the evacuated compound parabolic concentrator which is shown in Fig. 2, in which external compound parabolic concentrator (XCPC)

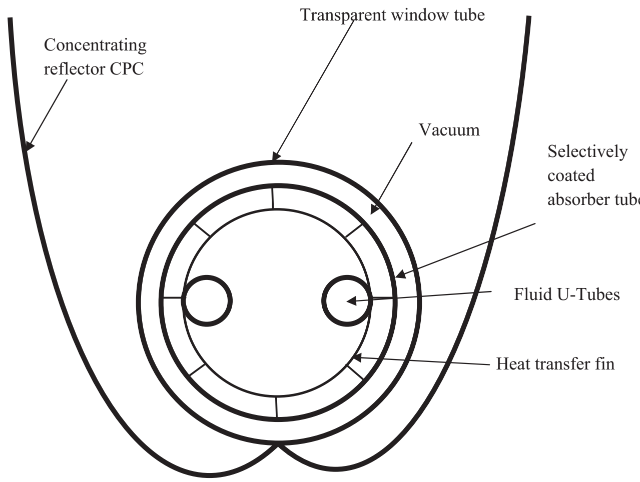


**Fig. 2.** Cross-sectional view of a basic stationary XCPC trough coupled to a Dewar-type evacuated tube [30].

incorporated with a Dewar-type evacuated tube. It comprised of two concentrating glass tubes, and the spaces between the tubes were evacuated. The outside surface of a glass tube was coated with selective surface. This tube was inserted into a larger-diameter domed glass tube. [30]. Sanil et al. [31] developed an Integrated Stationary Evacuated Concentrator (ISEC). It comprised of vacuum insulation; selective coating and compound parabolic concentrator combined together as a single unit that made an evacuated tube into the CPC. It was reported that the system could achieve optical and thermal efficiency of 65% and 50% respectively. Kim et al. [32] compared the performance of the tracking and stationary types of evacuated CPC solar collectors. The results showed that the thermal efficiency of the tracking type of evacuated CPCs was 14.94% higher than the stationary type of evacuated CPCs. Nkwetta et al. [33] conducted a comparative study between a flat single-sided absorber within a CPC (SSACPC) and a double sided absorber within a CPC (DSACPC). Both the models were coupled with the heat pipe. They concluded that the performance of the DSACPC was better. Li et al. [34] have compared two truncated external CPC (XCPC) solar energy collectors incorporated with the U- shape evacuated tube. Both the models have different half-acceptance angles and concentration ratios and it was found that the daily thermal efficiency of 6 × CPC was significantly better.

### *2.3. Various applications of CPCs*

CPCs are widely used for a variety of applications. Some of the recent developments of CPC solar collectors for various applications are given below. Suresh et al. [35] studied the thermal and optical characteristics of a truncated CPC for the potential application for the two-stage solar thermal power generation systems. Their study shows that the optical efficiency of CPC with the highly reflective surfaces to be 90% and above. Oommen et al. [36] designed a steam generation system incorporated with a pressure cooker powered by CPC solar collectors with half-acceptance angle of 23.5°. The result shows that the efficiency of the system was about 50%. The study of comparative performance of an asymmetric compound parabolic photovoltaic concentrator (ACPPVC) and a similar non-concentrating system was reported by Mallick et al. [37]. They concluded that the electrical conversion efficiency of the non-concentration was better than ACPPVC. Mallick et al. [38] presented a performance analysis of the air filled asymmetric compound parabolic photovoltaic concentrators. It was estimated that the maximum solar cell temperature has to be 95 °C for an incident insolation of 1000 W /m$^2$. Tchinda [39] developed a mathematical model to predict the thermal performance of a truncated CPC solar collector having a flat one-sided absorber for air heater application. The result shows that the obtained maximum temperature of the absorber and out flowing air was 118 °C and 72 °C respectively. Gonzalez et al. [40] designed the solar absorption cooling systems using a CPC solar collector and the activated carbon-methanol pair. The tubular receiver of a CPC included the sorption bed where only a section of the receiver was exposed to sunlight. They found that the COP of the system was 0.078 to 0.096. Buttinger et al. [41] developed a CPC for process heat application integrated with one absorber tube and reflectors inside a low pressure enclosure with an aperture of 2 m$^2$. They estimated its efficiency to be 50%. An advanced building integrated photovoltaic-thermal unit was proposed by Chemisana et al. [42]. This system comprised of a linear Fresnel lens as primary concentrator, a CPC as secondary concentrator and a PV-thermal module. Gang et al. [43] designed a low temperature electric generation system, equipped with a CPC and an Organic Rankin Cycle. Organic fluid was preheated by flat plate collectors prior to inflowing a higher temperature heat exchanger coupled with the compound parabolic concentrator. The two-stage heat storage units were made from two types of phase change materials with different melting temperatures. Harmim et al. [44] assembled a box-type solar cooker equipped with an asymmetric CPC. The CPC has 637 mm aperture width and 0.445 m$^2$ aperture area. The concentration ratio was 2.12. The result shows that maximum absorber-plate temperature and the inside air temperature were 140.5 °C and 118.4 °C respectively. Nkwetta et al. [45] performed an analysis of an internal low-concentrating evacuated tube heat pipe combined with a truncated CPC for the application of solar air-conditioning systems. They estimated its optical efficiency to be 79.13%. Jadhav et al. [46] proposed a novel compound parabolic concentrator for the application of Industrial Process Heat (IPH). A receiver pipe was placed below the common focus of two parabolas and close to the aperture. The geometrical acceptance angle was 3° and the temperature of steam was reaching up to 120 °C. Tanveer and Guyer [47] reviewed the application, design and operational parameters of CPC solar collector in wastewater treatment and water disinfection. Wang et al. [48] presented an analysis of a solar air heater powered by 10 linked solar collector panels. Each panel comprised a CPC coupled with a U-shaped copper tube heat exchanger installed in a glass evacuated tube and the maximum temperature was recorded as 200 °C.

In the foregoing discussion, the various developments of CPCs over the years and their potential applications have been discussed. The forthcoming section details with the different types of integrated compound parabolic concentrator storage solar water heaters (ICPCSSWHs) and also considers the various parameters that affect their performance.

## 3. Design, development and performance evaluation of various types of integrated compound parabolic concentrator storage solar water heater

Fig. 3 illustrates a systematic classification of ICPCSSWH systems. The ICPCSSWHs can be classified mainly according to the type of absorber used. In liberal terms, they can be separated into three major groups, namely: cylindrical absorber type ICPCSSWHs, inverted absorber type ICPCSSWH, and flat fin absorber type ICPCSSWH. Cylindrical absorber type ICPCSSWHs can further be grouped into two types. These are; single tank – ICPCSSWHs and double tank – ICPCSSWHs. Further, single tank – ICPCSSWHs can be sorted based on the type of reflector, viz., asymmetric reflector systems, symmetric reflector systems, three parabolic sections type ICPCSSWH and non-imaging cusp concentrator type ICPCSSWH. Likewise, double tank – ICPCSSWHs can also be classified into four types in terms of the reflector, viz., Symmetric reflector systems, asymmetric reflector systems, three reflector parts type ICPCSSWHs and two reflector parts type ICPCSSWHs.

### *3.1. ICPCSSWH systems with a single cylindrical water tank*

The cylindrical water storage tank of ICSSWHs can be mounted in a horizontal or vertical position inside the CPC collector trough. The first method corresponds to ICSSWHs with low height, for an aesthetical integration on building roofs, and their cylindrical water storage tank which can be thermally protected by using diverse methods. In the vertical mounting method, the satisfactory water temperature stratification can be achieved. Because this method is compatible with both horizontal and inclined roof system installations, as well as on building façades. The ICSSWHs with one or two cylindrical water storage tanks are lighter in weight and have somewhat lower optical efficiency, as they use CPCs to receive solar radiation on the aggregate or a large portion of their cylindrical surface, with the non-illuminated part of it being thermally insulated. This section presents a review of variety of ICPCSSWH incorporated with single cylindrical tank systems and their performance affected by different parameters.

#### *3.1.1. Single tank ICPCSSWH – asymmetric reflector*

The heat transfer losses from an ICSSWH can be reduced by employing an asymmetric reflector together with a cylindrical tank to produce a region of trapped warm air heated by the contact with the cylindrical tank surface. Tripanagnostopoulos et al. [49] constructed the two asymmetric CPC type ICSSWH (ICS-1 and ICS-2) with different thermal loss suppression techniques (Fig. 4). In ICS-1, the storage tank was completely surrounded in the trapping volume and accepted the solar radiation only from reflection of the mirror. But in ICS-2, the front half of the tank surface received direct solar radiation and back half of the storage tank had the trapping volume. The experimental works were conducted using two different mirrors (Stainless steel/ Aluminized mylar) and absorber surfaces (Black paint /Maxsorb Foil). The experimental results were compared with a symmetric CPC type ICSSWH. The experimental results show that ICS-1 with Maxsorb selective surface presented more efficient thermal performance than the other two systems and thermal loss of ICS-2 was higher as compared to other two models.

Tripanagnostopoulos et al. [3] designed another one asymmetric CPC type ICSSWH (Fig. 5) comprised of two parabolic reflector parts (AB) and (C′A′) and an involute part (BC). The cylindrical storage tank was insulated around 1/4 of the total surface area. The system has an acceptance angle and concentration ratio of 90° and 1.12 respectively. Better thermal projection and inverted absorber geometry of this system obtained thermal loss coefficient of 5.69 W/K, 5.81 W/K when using innox and aluminized mylar reflector respectively. It was found that better mean daily efficiency was achieved using aluminized mylar reflector.

Four different types of thermal insulation around the single horizontal cylindrical water tanks (Model–1: 1/4 insulated water tank, Model– 2: 1/8 insulated water tank, Model – 3: 1/4 insulated water tank, and Model– 4: 3/8 insulated water tank) incorporated with the truncated asymmetric type ICSSWHs were constructed and analyzed by Tripanagnostopoulos et al. [50]. All four cylindrical tanks were painted using matt black. Two different reflectors (Innox / Aluminized mylar) were used for experimental work. The experimental results of four models were compared with a FPTU and symmetric CPC type ICSSWHs. During non-collection period, the asymmetric CPC type ICSSWHs obtained lower values

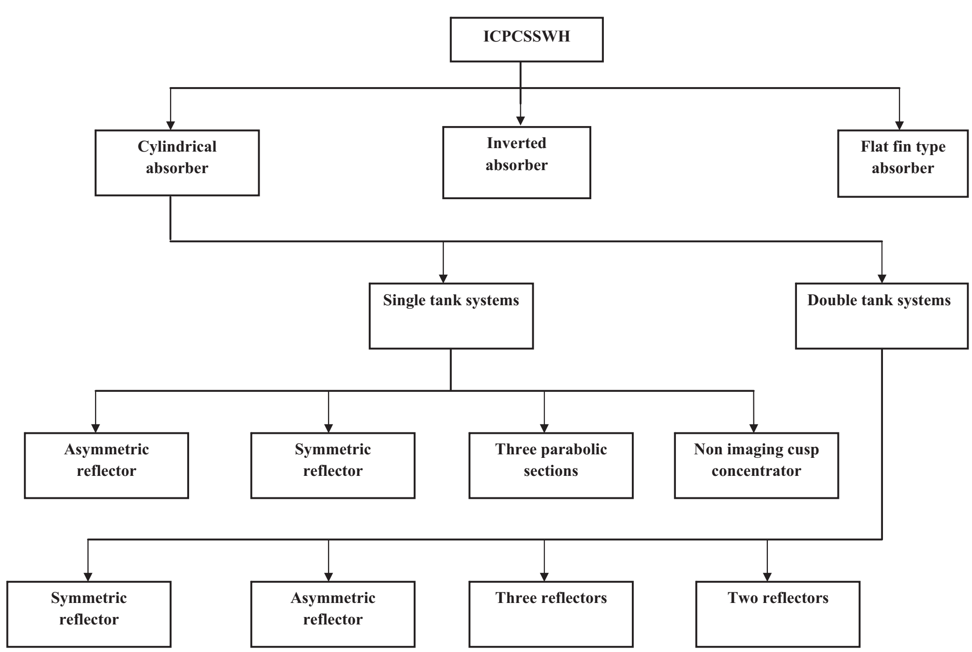


**Fig. 3.** Classification of ICPCSSWH systems.

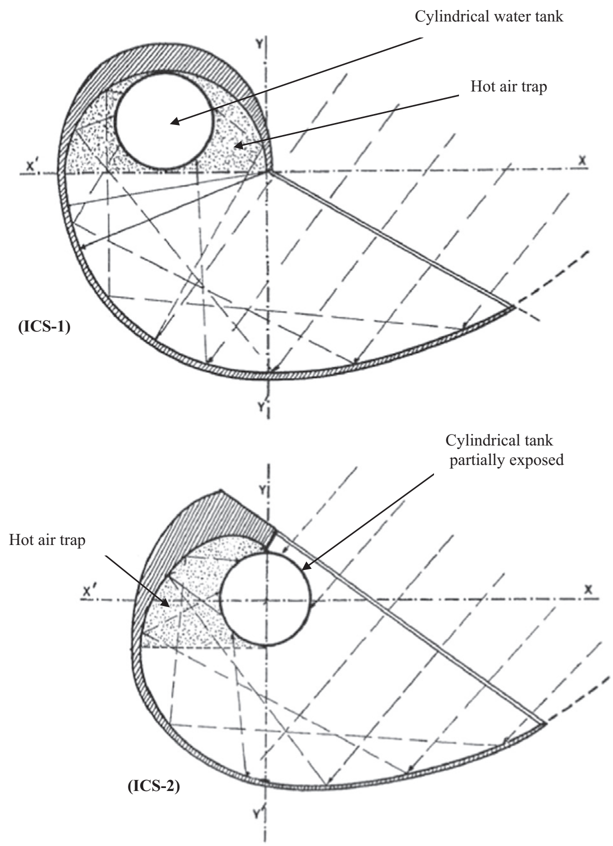


**Fig. 4.** Cross sectional view of the asymmetric CPC type ICSSWHs [49].

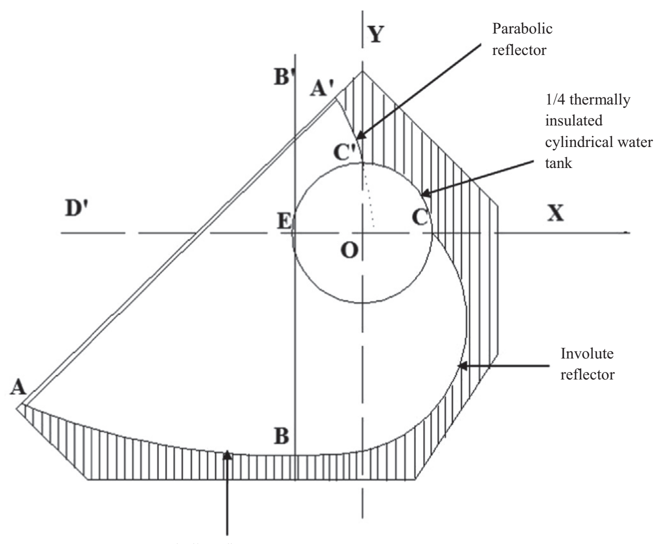


**Fig. 5.** Cross sectional view of an asymmetric CPC reflected a single cylindrical storage tank ICSSWH [3].

of thermal loss coefficient compared to symmetric CPC type ICSSWHs. Finally, the authors concluded that the Model- 2 and Model- 4 were presented good thermal performance among the four models.

A novel heat retaining method was proposed for a truncated asymmetric CPC type ICSSWH by Souliotis et al. [51]. The receiver had two concentric cylinders; where the space between the two was partially evacuated to decrease the heat losses and a small volume of water was stored in the inner cylinder. The outer surface of the cylindrical receiver was covered by Maxorb selective absorber film and it was partially exposed to solar radiation. The remaining receiver surface area was thermally insulated to improve heat preservation during the night. The thermal performance of the ICSSWH was compared to a FPTU. The maximum

water temperature found was 80 °C. They point out that the performance of the novel design was efficient during both day and night.

### 3.1.2. Single tank ICPCSSWH – symmetric reflector

ICSSWHs with symmetric CPC reflectors combining with non-uniform distribution of solar radiation on its absorbing surface resulted in an efficient water temperature rise within the storage tank. Tripanagnostopoulos et al. [3] designed an ICSSWH is shown in Fig. 6, in which a truncated symmetric CPC reflector had two parabolic (AB), (DA′) and two involute parts (BC), (C′D). A 1/4 thermally insulated horizontal cylindrical storage tank was mounted inside the reflector trough. The acceptance angle of the system was 90°. The outer surface of the water tank was painted using matt black. Both innox and aluminized mylar reflectors were tested and they found that the former had a low thermal loss coefficient and latter achieved a high mean daily efficiency.

Tripanagnostopoulos et al. [52] designed and constructed four ICSSWH models, two with involute and two with symmetric CPC reflectors, together with horizontal (East–West) and vertical (North–South) mounting of single cylindrical water storage tank. The experimental results show that ICSSWH with single horizontal cylindrical tank presented a satisfactory performance on the water temperature rise during day time and heat preservation in the cylindrical water storage tank during non-collection periods. They concluded that ICSSWH models with CPC reflectors had achieved higher mean daily efficiency than involute reflectors. To study the effect of total stored water ($V_T$), the ratios of the stored water volume per aperture area ($V_T/A_a$) and stored water volume per total surface area ($V_T/A_s$) on the thermal performance of the symmetric CPC type ICSSWHs, three experimental models with different diameters of water storage tanks were proposed by Souliotis et al. [53]. They found that the water temperature of the cylindrical tanks was increased inversely proportional to the parameter ratio $V_T/A_a$ during the day time and thermal loss coefficients were directly proportional to $V_T$ and parameter ratio $V_T/A_s$ during the night. The same team constructed 12 different types of symmetry CPC type ICSSWHs with the same diameter of water tanks, but two different CPC reflectors, absorbing surfaces and transparent covers (Single or/ and Double). The experimental results of these models were compared with two FPTU (Matt black/Selective absorbing surface). They pointed out that single tank- symmetric CPC type ICSSWHs with selective absorbing surface and high reflectance reflector performed close to FPTU systems both during the day and night hours. Souliotis et al. [2] studied the optical and thermal performance of an ICSSWH comprised of a single horizontal cylindrical storage tank mounted inside a truncated symmetric CPC reflector trough. The CPC had a truncation level of 46%. The optical performance of ICSSWH was studied using a Ray Tracing Method (RTM) and the Average Number of Reflections (ANR) method. The optical analysis of the ICSSWH was carried out for four different combinations of the transparent cover and the reflector surface. The results show that the upper part of the cylindrical storage tank surface collected the highest amount of the total absorbed solar radiation for all incident angles all over the year. Tripanagnostopoulos et al. [54] constructed four different types of ICSSWH with truncated symmetric CPC reflectors. Two CPC reflectors had an acceptance angle of 90° and other two had an acceptance angle of 60°, half of them without and the other half with a 1/4 thermally insulated around cylindrical water tank surface. The experimental results were compared with the two ICSSWH with symmetric involute reflectors with an acceptance angle of 180°. The system had one with a 1/4 thermally insulated cylindrical water tank and one without. All cylindrical water tanks had the same dimensions and horizontally mounted in the symmetric curved reflector troughs. They concluded that CPC type ICSSWH had an acceptance angle of 90° with 1/4 insulated tanks were more efficient during night times and with the thermal loss coefficient up to 30%. Three different types of ICSSWHs were designed and constructed with horizontal cylindrical water tanks and thermally insulated at the back side around 18.17% of their surface area [55]. Illumination parts of all the water tanks were coated with Maxorb selective surface. First experimental model (ICS1) comprised of an involute reflector with an acceptance angle of 180°. Second (ICS 2) and third (ICS 3) experimental models comprised of a CPC reflector with an acceptance angle of 90° and 60° respectively. All three models were tested using single and double glazed arrangements and experimental results were compared with a FPTU. The experimental results show that ICSSWH with single glazed systems reached higher thermal loss coefficient than double glass systems, while double glazed systems decreased the optical efficiency at daytime as well the thermal loss during non-collection periods. Out of all, ICSSWH with the double glazed and acceptance of 90° was found to be most efficient. Souliotis et al. [56] studied the performance of an ICSSWH using TRNSYS together with a “black box” modeling approach of Artificial Neural Network (ANN). Experimental data were gathered from a symmetric

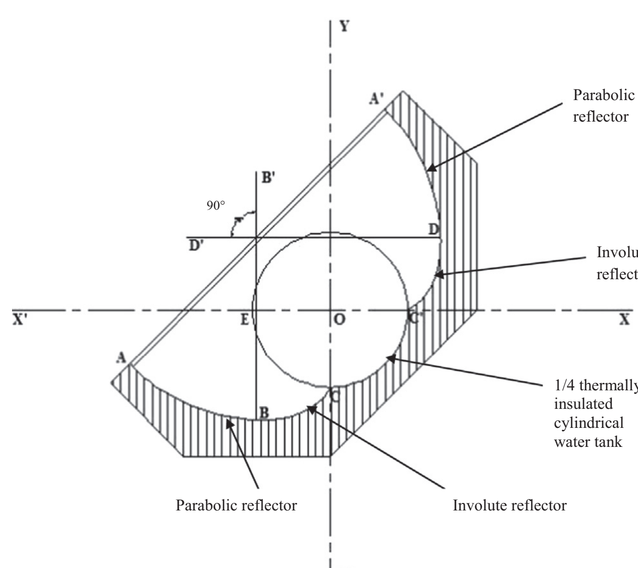


**Fig. 6.** Cross sectional view of a symmetric CPC reflected a single cylindrical storage tank ICSSWH [3].

CPC type ICSSWH to prepare the ANN. The annual performance of the ICSSWH was predicted by ANN techniques were used through the Excel interference (Type 62) in TRNSYS. The authors pointed out that recommended method was complicated to model analytically. Chaabane et al. [57] numerically investigated the thermal performance of an ICSSWH with a single horizontal cylindrical water storage tank mounted in CPC. They developed two 3D numerical models using Fluent 6.3. The geometry of the first numerical model was based on the solar water heater experimentally investigated by Chaouachi and Gabsi. The second numerical model was made up for a cylindrical storage tank equipped with radial fins of rectangular profile. They also investigated different depth of fins to improve the thermal performance of this system. During daytime, the increase of the fin's depth contributed to the higher water temperature and reduced thermal loss coefficient. But the modified storage tank allowed for higher thermal losses during night time.

#### *3.1.3. Single tank ICPCSSWH– three parabolic sections*

Helal et al. [58] designed a CPC type ICSSWH shown in Fig. 7, in which a single cylindrical horizontal tank was placed in a CPC reflector composed of three parabolic branches. The CPC had 1180 mm aperture width, 1.084 m depth and concentration ratio was 1.05. The addition of the third parabolic branch increased the number of reflection to the absorber. They estimated its average number of reflections to the absorber to be 1.15. The experimental result shows the thermal coefficient per aperture area varied between 3.7 and 3.9 W/m$^2$K..

#### *3.1.4. Single tank ICPCSSWH– non-imaging cusp concentrator*

Truncation of non-imaging cusp reflectors which concentrate sunlight onto cylindrical absorbers makes collector designs which are more cost-effective through considerable decrease in mirror height and length with small decrease in concentration ratios. Kalogirou [59] designed and investigated an ICSSWH which contains a non-imaging cusp type concentrator and a horizontal cylindrical water tank. A computer code was developed for modeling and optimization of ICSSWH. The result shows the initial cost of the system had 13% lower compared to flat plate solar collector.

On the basis of the above discussions on various types of single tank ICPCSSWH, the following conclusions can be inferred:

- Fabrication of an ICSSWH did not need high technology and its cost of installation was more economical.
- CPC reflector gives effective solar radiation concentration, depending on its acceptance angle and truncation level.
- Horizontal water tank combined with a CPC reflector trough produces the system concentration ratio of $C > 1$.
- The temperature stratification of vertical water storage tank was better than horizontally oriented water tank.
- Horizontal orientated tank incorporated to the CPC reflector with an acceptance angle $\theta = 60^\circ$ or $90^\circ$ is more practical.
- The vertical (North–South) oriented storage tank contributed to effective water temperature stratification, while horizontal (East–West) storage tank mounting results to better thermal protection.
- Using of selective absorbing surface along with the high reflectivity reflector and double glazing with high transmissivity combination increases the thermal performance of the ICSSWH.
- ICSSWHs integrated with the asymmetric CPC reflectors contribute to satisfactory water heat preservation during the night than symmetric CPC reflectors.

### *3.2. ICPCSSWH systems with double cylindrical water tank*

Unlike single tank- ICPCSSWH, the non-uniform distribution of solar radiation on the absorber surface can also be efficiently employed for attaining water temperature stratification by placing two horizontal cylindrical water storage tanks connected in series in the ICPCSSWH. The first tank was joined directly to the water mains and operates as system preheater, while second tank acts as final water heating. In the following sub Sections (3.2.1–3.2.4) a variety of double tank ICPCSSWHs is reviewed and classified based on the reflector.

#### *3.2.1. Double tank ICPCSSWH – symmetric reflector*

Kalogirou [60] investigated experimentally a CPC type ICSSWH with a cylindrical water tank which had a diameter of 110 mm and was mounted between glass and main cylindrical water tank with diameter and volume of 200 mm, and 65 litres respectively (Fig. 8). The modified system was compared with a single cylindrical water tank which had a diameter of 200 mm which connected with a CPC reflector. The double tank system increased 30% of the storage capacity than single tank system and also reduced night time thermal losses. The experimental results show that the modified system offered 12 litres of hot water more than single cylinder

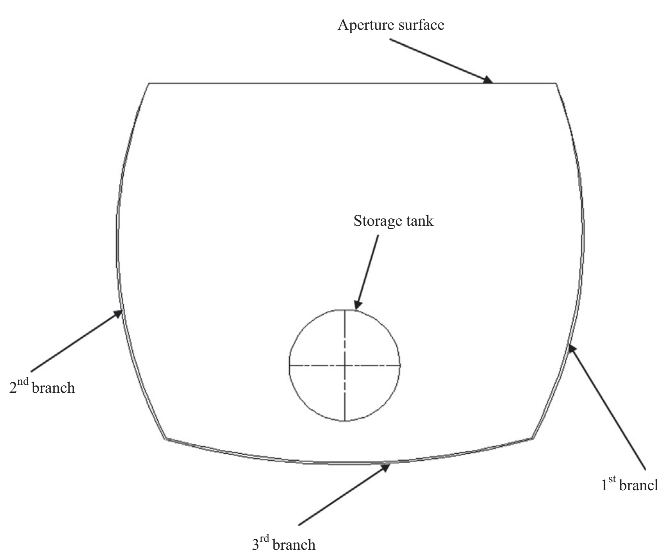


**Fig. 7.** Front view of an ICPCSSWH [58].

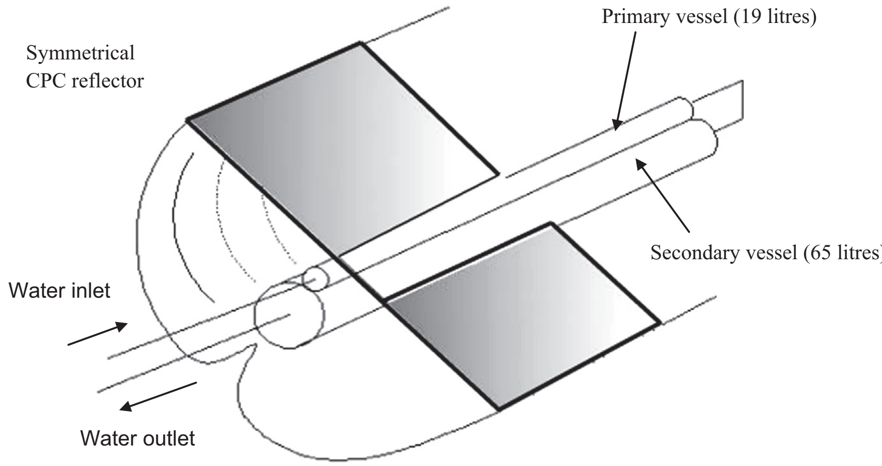


**Fig. 8.** Schematic view of a double tank ICSSWH with a symmetric CPC reflector [60].

solar water heater. The modification of this system was increased the cost by 8%.

### 3.2.2. Double tank ICPCSSWH – asymmetric reflector

The combination of asymmetric CPC reflectors with double cylindrical water storage tanks is a notable subject for the absorber illumination, water heating and thermal loss suppression. The asymmetric CPC reflectors result in a different distribution of solar radiation on them. Tripanagnostopoulos et al. [61] designed a truncated asymmetric CPC type ICSSWH had two horizontal water tanks A1 and A2. Asymmetric reflector comprised of two parabolic parts (BF and DE), a circular part (BA) and one involute part (AD) as shown in Fig. 9. The cylindrical water tanks were made up of galvanized iron and painted using black paint. Polished stainless steel used as a reflector. They found that the maximum mean daily efficiency was 80%.

Tripanagnostopoulos et al. [62] constructed an asymmetric CPC type ICSSWH (DTS –I) with two horizontal cylindrical water tanks and an asymmetric CPC reflector. The novel design increased 70% of non-uniform solar radiation on the water tank A2. Thermal loss coefficient of this system was 6.3 W/°C at $\Delta T_{m,\ N}$=28.3 °C. The same team [62] constructed another one asymmetric CPC type ICSSWH(DTS-II) comprised of an asymmetric CPC mirror, two horizontal cylindrical water tanks(A1 and A2), a transparent cover, thermal insulation at the external reflector surface and two side mirrors with external insulation. Better thermal insulation of water tank A2 had 35% higher thermal preservation than A1 and overall thermal loss coefficient was 5.6 W/°C at $\Delta T_{m,\ N}$=28.9 °C. Both the systems are illustrated in Fig. 10.

Tripanagnostopoulos et al. [3] assembled an asymmetric CPC type ICSSWH (Fig. 11). This reflector comprised of two parabolic parts (AB, A′C′) and a circular part (BD). The cylindrical water tank T1 was placed on the upper part of the system and cylindrical water tank T2 was arranged below the first one. The top tank was insulated around 1/8 of the total surface area. The hot air trap was created between cylinders and reflector due to 1/8 thermally insulated upper placed water tank. This system achieved a mean daily efficiency of 36%, 41% with innox reflector and aluminized mylar reflector respectively. The thermal loss coefficient was recorded as 6.50 W/K for innox reflector and 6.69 W/K for aluminized Mylar reflector at $\Delta T_{m,\ N}$=40 °C.

Tripanagnostopoulos et al. [8] designed two different models of ICSSWH (DTS-C1 and DTS-C2) consisting of two water tanks incorporated with an asymmetric CPC reflector. A parabolic reflector was placed on the top of the both the models and two circular reflectors were joined with the upper water tank of model DTS- C1. Reflector parts of both models were made up of aluminized mylar and water tanks were painted using matt black absorbing surface. In both the models, lower placed tank received higher amount of solar radiation than an upper tank. The results show that thermal loss coefficient of DTS-C2 was lower than DTS-C1.

### 3.2.3. Double tank ICPCSSWH – three reflectors

Tripanagnostopoulos et al. [3] constructed an ICSSWH with two water tanks. The upper placed water storage tank T1was insulated 5/12 of the total surface area and received reflected solar radiation from two parabolic parts and an involute reflector part. The lower placed cylindrical water storage tank *T*2 was insulated 7/24 of the total surface which received solar radiation from a reflector comprised of one parabolic part and an involute part. Two different reflector materials (Innox / Aluminized mylar) were employed for an experimental analysis. The experimental results show that the aluminized mylar reflector system exhibited higher mean daily efficiency than innox reflector system.The thermal coefficients were recorded as 7.04 W/K and 7.40 W/K for innox and aluminized mylar respectively.

Tripanagnostopoulos et al. [8] studied two ICSSWHs (DTS- A1 and DTS- A2) comprised of mainly three reflector parts: (1) two of CPC geometry combined with the two horizontal cylindrical storage tanks, and (2) one parabolic at the top portion of the systems. The lower reflector part is an asymmetric CPC together with one parabolic part and an involute part. The CPC geometry of both the systems was same, but they differ only in the upper placed reflector as shown in Fig. 12. The experimental results show DTS- A1 obtained a higher thermal coefficient than DTS- A2.

### 3.2.4. Double tank ICPCSSWH – two reflectors

Tripanagnostopoulos et al. [8] constructed another two (DTS-B1 and DTS-B2) models. Both the models (Fig. 13) comprised of two reflector units: (1) one symmetric CPC together with the lower placed cylindrical water tank, and (2) one parabolic part combined with the upper placed cylindrical water tank but different thermal insulation around the upper placed water tanks only. They concluded that the mean daily efficiency of DTS - B2 observed more than 75% and the thermal loss coefficient of DTS-B1 was higher than DTS-B2.

Kessentini et al. [7] carried out both an experimental and numerical analysis of a model (DTS-B1) proposed by Tripanagnostopoulos et al. [8]. Numerical results were compared with experimental results and found to be in good agreement. From the numerical results, they found that the increase of concentrator reflectivity considerably increases the yearly diurnal heat gain by 3%. The use of low emissive absorber and double glazing arrangements reduced the overall heat loss of the ICSSWH by 47%.

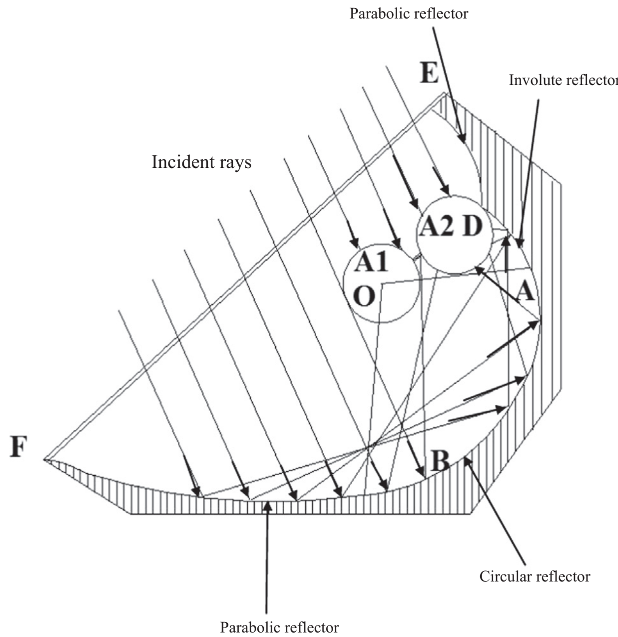


**Fig. 9.** Cross sectional view of an asymmetric CPC reflected a double cylindrical storage tank [61].

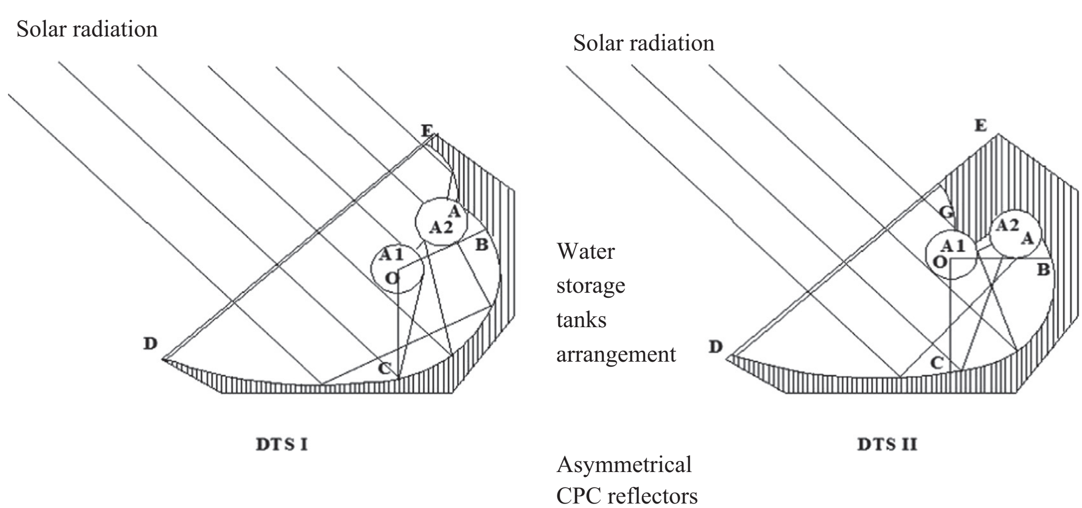


**Fig. 10.** Two different types of double tank Integrated Collector Storage (ICS) system [62].

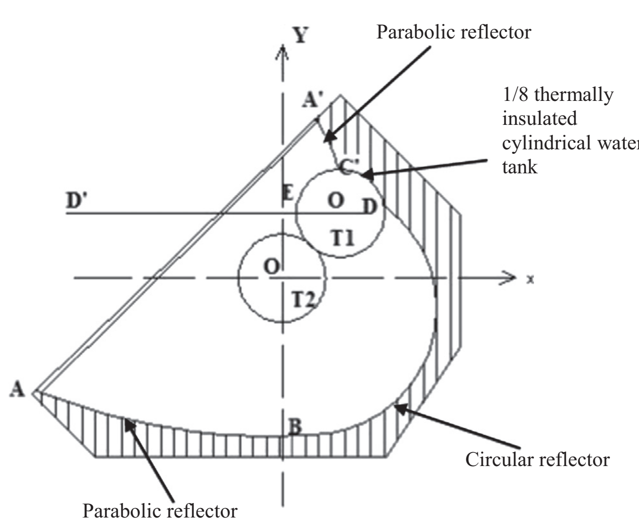


**Fig. 11.** Double tank asymmetric reflector type ICPCSSWH with a 1/8 insulated top water tank [3].

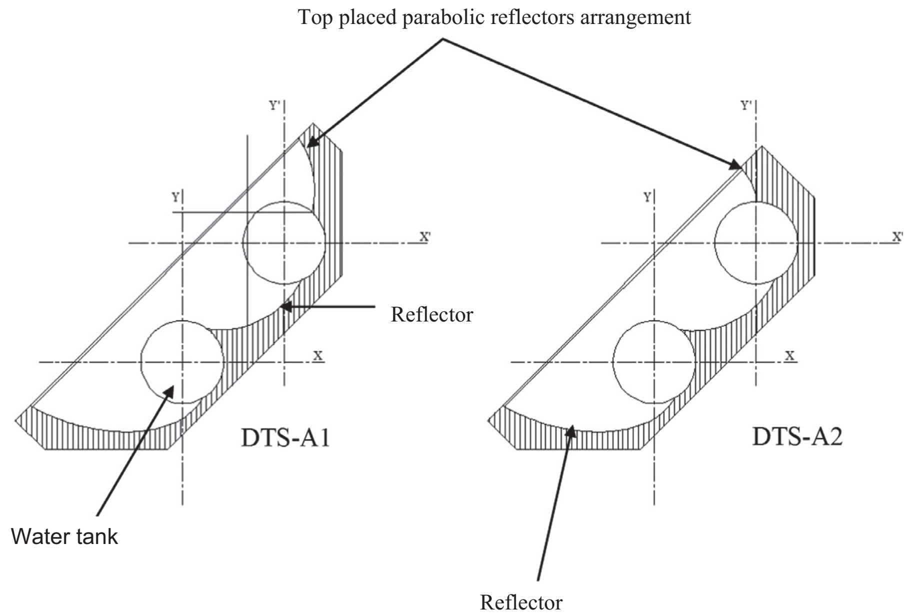


**Fig. 12.** Cross-sectional view of the double tank ICPCSSWH systems with three reflectors [8].

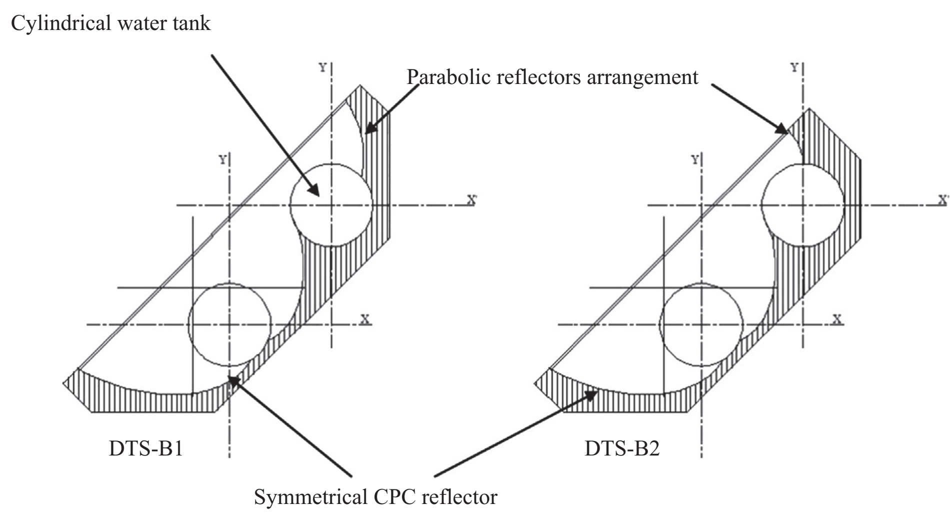


**Fig. 13.** Cross sectional view of the double tank ICPCSSWH systems with two reflectors [8].

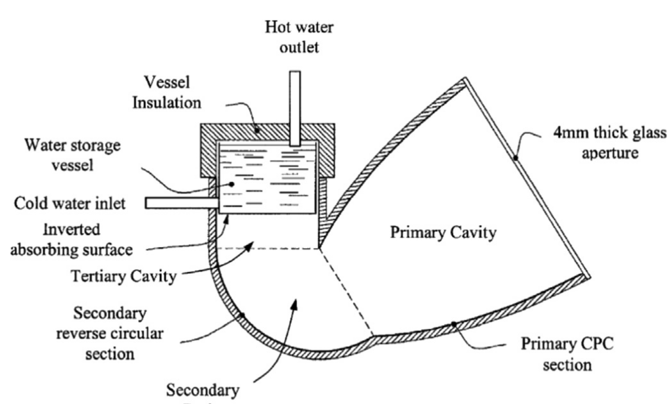


**Fig. 14.** Cross-sectional view of an inverted absorber type ICPCSSWH [63].

The above discussion of double tank ICPCSSWH systems in the open literature, allow the author to draw the following conclusions.

- Separations of the stored water in two tanks are placed at different height, which contributed to satisfactory water temperature stratification.

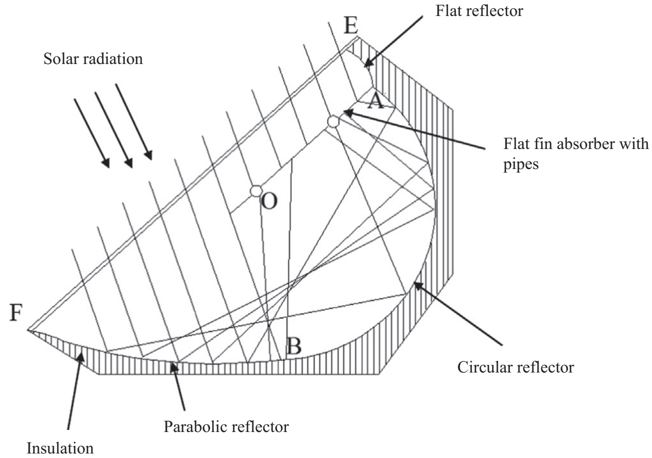


**Fig. 15.** Cross sectional view of an ICPCSSWH with a flat fin type absorber [61].

**Table 1**
Advantages and disadvantages of different ICPCSSWH systems.

| ICPCSSWH systems | References | Advantages | Disadvantages |
|---|---|---|---|
| Single tank ICPCSSWH – Asymmetric reflector | Tripanagnostopoulos et al. [49] | – Reduce thermal losses<br>– Better overall efficiency<br>– Sufficient temperature preservation during night | – Requires more material for the construction of the mirror envelope<br><br>– Low optical efficiency |
| | Tripanagnostopoulos et al. [3] | – Moderate water temperature stratification | – Asymmetric reflector geometry enhances system depth |
| | Tripanagnostopoulos et al. [50] | – low manufacturing cost<br>– Better water temperature preservation during the night.<br>– Mean daily efficiency close to FPTU. | – Requires effective heat protection of their water storage tank |
| | Souliotis et al. [51]. | – Effective thermal performance | – Low optical efficiency occurs in winter |
| Single tank ICPCSSWH– Symmetric reflector | Tripanagnostopoulos et al. [3] | – Moderate system depth<br>– Sufficient temperature preservation during night<br>– Cost-effective | – High conduction and convection losses during non-collection periods |
| | Tripanagnostopoulos et al. [52] | – Simple construction | – Requires anodized aluminum reflectors, selective absorber, low iron glass and double glazing for efficient operation during the day and non-collection periods. |
| | Tripanagnostopoulos et al. [54] | – Cost-effective<br>– Simple construction | – High thermal losses during the night |
| | Chaabane et al. [57] | – High water temperature during day time | – Higher thermal losses during non-collection periods |
| Single tank ICPCSSWH– Three parabolic sections | Helal et al. [58] | – Better thermal efficiency<br>– Increases the number of reflected rays to the absorber | – High thermal losses during the night |
| Single tank ICPCSSWH– Non-imaging cusp concentrator | Kalogirou [59] | – Cost-effective | -Requires reduced height of the system for effective operation |
| Double tank ICPCSSWH – Symmetric reflector | Kalogirou [60] | – Increases storage volume<br>– Better draw-off characteristic | – Low end of day temperature<br>– Requires additional capital cost |
| Double tank ICPCSSWH– Asymmetric reflector | Tripanagnostopoulos et al. [61] | – Cost-effective | – Requires a long time to attain thermal equilibrium<br>– High thermal loss |
| | Tripanagnostopoulos et al. [62] | – Cost -effective | – Requires second glazing and an electrical heater during cloudy days |
| | Tripanagnostopoulos et al. [3] | – Inverted absorber reduces the thermal losses of the system | – Low optical efficiency<br>– High system depth |
| | Tripanagnostopoulos et al. [8] | – Satisfactory conservation of hot water temperature during night | – Low mean daily efficiency |
| Double tank. ICPCSSWH– Three reflector systems | Tripanagnostopoulos et al. [3] | – Low optical losses<br>– low manufacturing cost<br>– Sufficient water temperature stratification during both day and night | – Requires effective heat protection |
| ICPCSSWH– flat fin absorber | Tripanagnostopoulos et al. [61] | – Cost-effective<br>– Short response time for steady state operation. | – Requires a heat removing fluid and a heat exchanger. |

- Double tank CPC type ICSSWH with symmetric CPC reflectors produced same illumination on both the storage tanks, while asymmetric reflectors created a different distribution of solar radiation on each tank.
- Double tank ICSSWH has better stratification than a single tank system.
- ICSSWHs with asymmetric CPC reflectors and double horizontal cylindrical storage tanks achieved satisfactory mean daily efficiency and effective water temperature stratification inside the storage tank.

### 3.3. ICPCSSWH – inverted absorber

One of the vital challenges in ICSSWHs is to decrease the thermal losses in order to decrease the convective and radiative losses from the absorber. Radiative losses can be decreased by selective absorber coatings; however, this will not increase ICSSWH's performance greatly unless convection losses are suppressed at the same time. The latter can be achieved either by evacuation or inverted absorber. Smyth et al. [63] presented the experimental performance of an inverted absorber ICSSWH (IAICSSWH). The schematic view of IAICSSWH is shown in Fig. 14. This type of water heater comprises of two main parts, namely: (1) a vessel, (2) one CPC enlarged with a 120° reverse circular reflector and a straight reflector part at the exit of the circular reflector. The vessel was made up of aluminum sheet. The vessel consists of an inverted absorbing surface coated with a selective absorbing film and exposed surfaces are covered using polystyrene insulation. Truncated CPC made the aperture inclination angle of 60° from the horizontal. The performance of the ICSSWH was investigated using a solar simulator and transparent baffles located at different positions within the collector cavity. Test results showed that thermal losses considerably reduced using baffles positioned at the upper portion of the outlet aperture of the CPC without reducing its optical efficiency.

### 3.4. ICPCSSWH–flat fin absorber

The shape of an absorber is an important element that influences the thermal performance of ICSSWH. Usually, solar radiation is absorbed by the absorber plate and transferred to the working fluid. In some configurations, radiation is directly taken up by the fluid. Two primary types of absorbers were used for ICPCSSWHs: the tubular absorber and fin type with a pipe. Fig. 15 illustrates the fundamental features of a flat fin absorber type ICPCSSWH [61]. It comprised of an asymmetric truncated CPC type mirror and a flat fin absorber with pipes. The CPC mirror was made up of three important parts: (1) one parabolic part (BF), (2) one circular part and (3) one flat reflector (AE). The front and inverted absorber surfaces were coated using selective and black paint respectively. This system had two flow channels, one operated as pre-heater and another acted as main heater. The reflector parts were made using aluminized foil. This system achieved a maximum efficiency of 80%.

## 4. Conclusions

This paper reviewed the compound parabolic concentrator (CPC) and its applications in integrated collector storage solar water heaters (ICSSWHs). A systematic classification of ICPCSSWH is evolved. The broad variety of practical realised design and performance of ICPCSSWHs are reviewed. Three board groups of ICPCSSWHs can be identified, viz., cylindrical absorber type ICPCSSWHs, inverted absorber type ICPCSSWH and flat fin absorber type ICPCSSWH. Table1 summarizes the advantages and disadvantages of various types of ICPCSSWH. From this review, it is found that the thermal performances of CPC type ICSSWH systems are effective during day time; however during the non-collection periods their performance is limited. But also they are simple in construction and cheaper than FPTU and could be considered promising domestic hot water heaters and their optimization could make them suitable for progress and practical use.

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